"Sojourner"
The Mars Pathfinder Microrover Flight Experiment

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Abstract:

The Microrover Flight Experiment (MFEX) is a NASA Office of Space Access and Technology flight experiment of mobile vehicle technologies, whose primary mission is to determine rnicrorover performance in the poorly understood planetary terrain of Mars. On July 4, 1997, the microrover landed on Mars and began its mission, after deployment from the Mars Pathfinder (MPF) lander. At this writing the microrover has been operating on the surface of Mars for the past 50 sois (I sol = I Martian day) completing both its nominal and extended mission objectives. The microrover continues in its mission to conduct a series of technology experiments such as determining wheel-soil interactions, navigating, traversing and avoiding hazards, and gathering data which characterizes the engineering capability of the vehicle (thermal control, power generation performance, communication, etc.). In addition, the microrover carries an alpha proton x-ray spectrometer (APXS) which when deployed on rocks and soil determines element composition. lastly, to enhance the engineering data return of the MPF mission, the microrover images the lander to assist in status/damage assessment.

Introduction:

Each of the following sections of this paper describe, by subsystem, the design, implementation and capabilities of the MFEX (named 'Sojourner") rover.

Mobility:

The MFEX rover is an 10.5kg, 6-wheeled vehicle of a rocker bogey design derived from the 'Rocky' series of vehicles developed at JPL. Each wheel of the rover is 13cm in diameter by 6cm wide. The 4 front and rear wheels are independently steered, providing the capability to turn in place (the rover has a 74cm turning diameter-j. .

The rocker-bogey suspension system allows the vehicle to traverse obstacles more than a wheel diameter in sire. 1 he stainless steel cleats on each aluminum wheel provide the traction necessary to scramble over rocks. The surface pressure of approximately 0.23psi (on Mars) allows the vehicle to cross soft, sandy surfaces.

Each wheel is independently actuated by a Maxon RE0 16 motor. which at a 2000: I gearing ratio, has been shown to require 116mA@15.5V to produce 9in-lb of torque at -80degC. As a consequence, assuming a distribution across the 6 wheels of 2 wheels each producing 9in-lb, 2 wheels each producing 4.5in-lb, and the remaining 2 wheels operating at no load, less than 8.5W is required to drive the vehicle at -80degC. As a measure of comparison, at the nominally warmest temperature on a given sol at Mars of 0degC, less than 2W is required to drive the rover-. Also, adequate margin is present in the motors and gearing so that, in a step climbing exercise, a single wheel can lift the weight of the rover on Mars. Stall torque for these motors at -80degC is 110in-lb, more than a factor ot' 10 above the torque (of 9in-lb) required at a wheel to drive the vehicle.

At -80degC and no load conditions, the geared motors produce approximately 0.9RPM, resulting in a vehicle which has a top speed of 0.4m/min at that temperature. At higher temperatures and similar no load conditions, greater speeds are possible. During steering, the top speed is 7deg/sec.

The rover is 65cm in length, 48cm wide and 30cm tall in its deployed configuration (neglecting the height of the UI If antenna), The rover is stowed on a lander petal for launch and during the cruise-to-Mars phase of the MPF mission. In this stowed configuration, the rover height is reduced to 19cm. in this configuration, the rover has been tested and shown to withstand static loads of 66g, consistent (with margin) with the less than 40g expected at impact upon landing on Mars. At deployment, the lander fires cable cutting pyres, releasing tiedowns which restrain the rover to the stowed configuration. Under command, the rover drives its wheels, locking the bogeys and deploying the antenna so that the deployed configuration is achieved,

In the deployed configuration, the rover has ground clearance of 1 5cm. The distribution of mass on the vehicle has been arranged so that the center of mass is nearly at the center of the body (the Warm Electronics Box (WEB)) and at a height at the base of the WEB. As a consequence, the vehicle could withstand a tilt of 45deg in any direction without over-turning, although fault protection limits prevent the vehicle from exceeding tilts of 35deg during traverses.

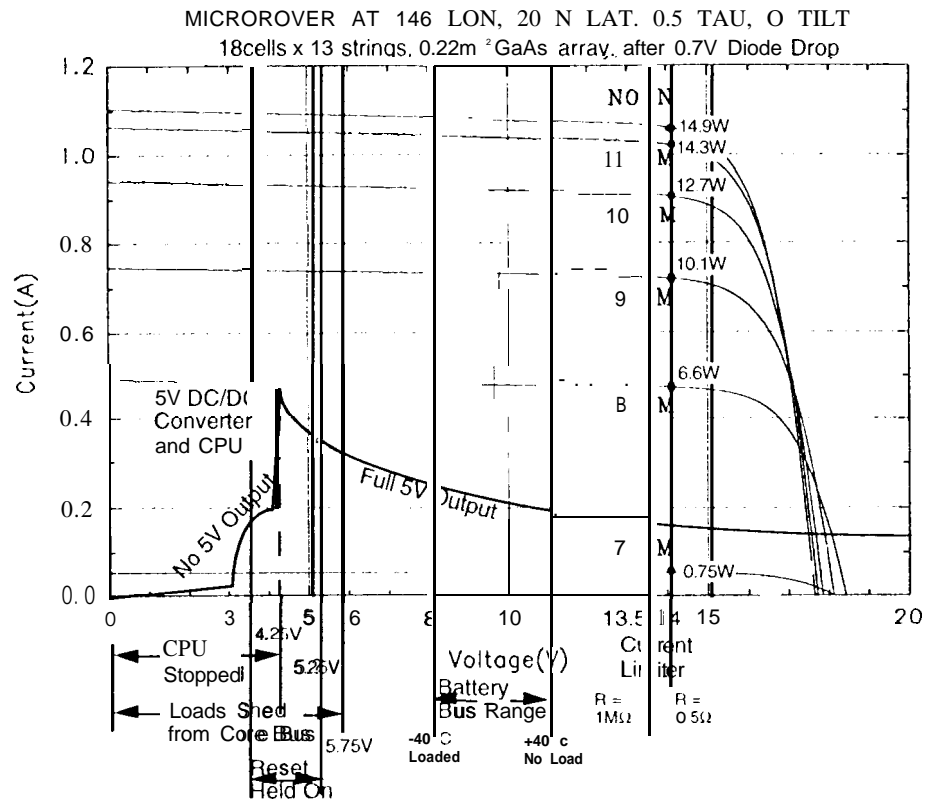Figure 1 : Mars Pathfinder Micmrover Flight Experiment (MFEX)
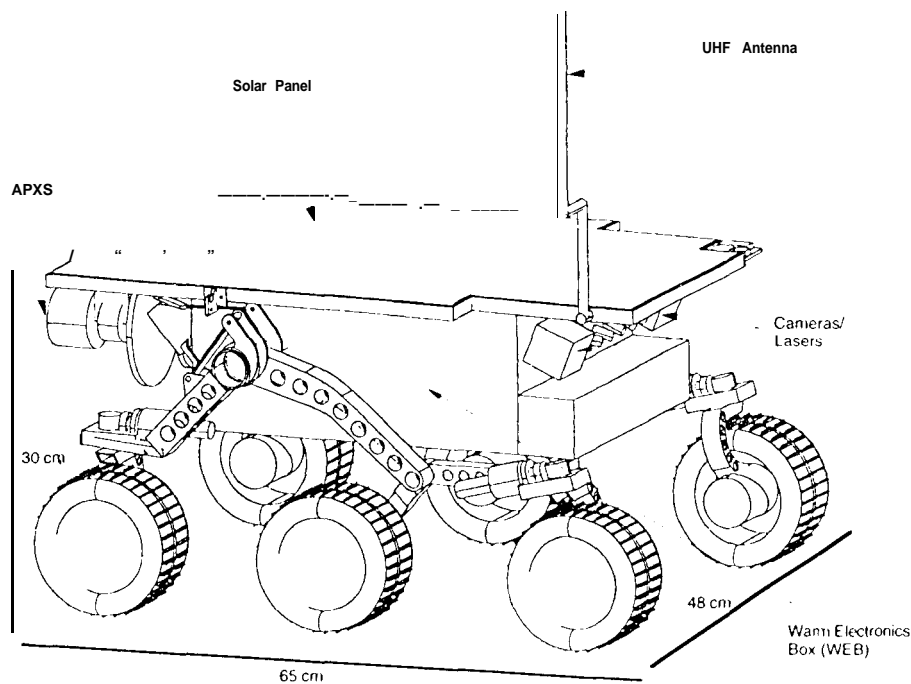
Power:

MFEX is powered by a 0.2sqm solar panel comprised of 13 strings of IS, GaAs cells each of size 2cm by 4cm. At mid-sol at the 19.5deg north lattitude landing site for MPF, this solar panel, untilted produces nearly 15W peak power (see Figure 2). The solar panel is backed by 9 LiSOCL₂ D-cell sized primary batteries, providing up to 300W-hr [It'energy. During the day, on-board computer control determines if sufficient solar panel power is available to perform a given commanded action (e. g., driving, imaging, etc.). Only it'the activity can be adequately supplied solar power will the function be initiated. However,

particularly while moving. shadows or tilt of the vehicle can reduce solar panel production. Consequently, the batteries are enabled during driving and at other times during the day, providing power to complete activities when solar panel power is not sufficient. As a result, the combined panel/battery system allows the rover power users to draw up to 30W of peak power (mid-sol).

Figure 2 : Solar Panel Performance and Electronics Protection for the CPU

MICROROVER AT 146 LON, 20 N LAT. 0.5 TAU, O TILT
18cells x 13 strings, 0.22m² GaAs array, after 0.7V Diode Drop

The solar panel provides more than 10W for 6hrs each day. Tl : daily requirements for individual rover functions are given in Table 1. The average panel daily energy production is 104 W-hr.

Power regulation is provided by a set of converters and regulators receiving power from the unregulated power bus supplied by the combination of solar panel and battery power. Certain power users (motors, heaters) require no regulation. These users are supplied via a current limiter which minimizes energy loss and ensures at least 13.5V of power supplied by the solar panel (with 14V as the nominal peak power point). When it can be anticipated that these users require power beyond that supplied by the solar panel (for example during motor startup transients), a special 'bypass switch' is enabled supplying battery energy directly to these users. Other users are supplied from regulators or converters. enabled under computer control.

The computer (CPU and memory) are a special case for power regulation since transient power supply anomalies can occur at early morning and bite afternoon conditions. A 5V converter regulates power supplied to the computer. In early morning. as the solar panel begins to produce power, a power monitor circuit holds the CPU in reset until adequate energy is available (i.e., the 5V converter is in regulation) to supply power for computation functions. In late afternoon, when solar energy is anticipated to drop below

computing requirements, the computer places itself in idle mode, In this mode, the computer awaits the 5V converter to drop out of regulation, effectively shutting down the CPU.

Table I: MFEX Power Requirements

Energy Required	Function	Time and Calculation
7.51 W-hr	motor heating: 1 motor at a time	= 7.51W x 1hr
5.63W-hr	motor heating: 2 motors at a time	= 11.26W x 0.5hr
6.92W-hr	driving (extreme terrain @-80degC)	= 13.85W x 0.5hr
1.83W-hr	hazard detection	= 7.33W x 0.25hr
0.45W-hr	imaging (3 images @2min/image)	= 4.5W x 0.1hr
1.2W-hr	image compression (compress 3images@ 6 min/image)	= 3.7W x 0.3hr
5.2W-hr	6Mbit communication @50min/sol	= 6.27W x 0.8hr
0.63W-hr	42, 10 sec health checks during day	= 6.27W x 0.1hr
15.0W-hr	remainder of 7 hr daytime CPU operation	= 3.7W x 4hr
50W-hr	WEB heating (as needed)	= 50W-hr
95W-hr		

Additional protection for the computer is provided by the 'load shed' circuit. This circuit senses voltage dropping below 5.75V. In this case (no battery backup provided and loads exceed capabilities of the solar panel) the 'load shed' circuit disables converters and regulators other than the 5V converter supplying the CPU, effectively shedding users from the power system. An interrupt is also set as a flag for the CPU. in servicing the interrupt, the computer determines which load caused the 'load shed' event and generates a report for ground operator analysis.

Finally, power for night-time operations is supplied by the batteries. An alarm clock can be set by the computer which places power from the batteries on the main power bos at a commanded or scheduled time. Power on the bus removes the reset condition on the CPU (subject to the power monitor) and allow's the computer to perform a night-time activity. The computer can 'go back to sleep' by removing power from the batteries to the power bus.

Thermal Control:

On Mars, MFEX components not designed to survive ambient temperatures (- 110degC during a Martian night) are contained in the Warm Electronics Box (WEB). The WEB is constructed using solid silica aerogel as insulation, lining an epoxy sheet and spar box. The insulation is of density approximately 20mg/cc with additional 20mg/cc aerogel crushed into a Nomex honeycomb top of the WEB. This top also serves as the substrate for the MFEX solar panel. A high emissivity gold coating serves as the exterior of the WEB. The WEB is heated each sol with a combination of 3 Radioactive Heating Units (RHUs), electronics waste heat and resistor array heat under computer control. Thermal capacity and RHU heat, distributed to components through thermal strapping, keeps the WEB above the minimum operating temperature of -40degC through the eight. The average thermal loss is required not to exceed 2W(50W-hr per sol) beyond the RHU supplied heat.

As a consequence of the testing conducted during the qualification program for the rover, no resistor array heating is planned during the mission : the electronic waste heat and RHUs suffice to provide the performance shown in Figure 3. The performance of only one component, the radio modem, has been demonstrated as affected by temperatures within the nominal temperature range (-40degC to +40degC) within the WEB. During testing, modem performance (as determined by bit error rate) degraded when the unit temperature dropped below -25degC. A 78ohm (2.5W at 14V) heater is configured with the modem

and operated under computer control to raise the temperature of the modem above -15degC to ensure' performance.

Outside of the WEB no active thermal control is planned during the mission. However, motor performance (as determined by torque output for power input) improves as the temperature of the motor increases, No motor is operated below -80degC and operation above -60degC is expected during the 6 hours per sol when sufficient power from the solar panel alone is available to move the rover (panel production above 10W). A 157ohm (1 .2W at 14V) heater is supplied with each actuator (e.g., wheel, steering motor and APXS deployment device) to allow heating which ensures motor performance outside of the expected daily driving period or during periods of off-nominal environment conditions.

Temperature is monitored through 13 temperature sensors distribute both inside and outside the WEB on the rover. These are shown in Table 2.

Table 2: MFEX temperature sensor locations

Total	location
3	One on each of the three battery cases
1	Modem
1	Power electronics board
1	CPU and 1/0 electronics board
1	WEB wall
2	One on each of the front wheels
3	One on each of the three cameras
1	Solar panel

During the cruise phase of the mission, MFEX is planned to be powered only twice, once shortly after launch and once a few days before entry at Mars, and for only a few minutes in each instance. The primary thermal control function during cruise is rejection of heat output by the RHUs inside the WEB. This is accomplished by the use of a thermal strap that connects the RHUs to a fixture at the bottom of the WEB. This fixture is in turn in contact with a thermal strap connected to the coolant loop provided at each petal of the lander. This coolant loop provides thermal control for the lander as a whole throughout the cruise phase of the mission. The connection between the fixture at the bottom of the WEB and the thermal strap at the lander petal is broken when MFEX achieves its deployed configuration. After landing on Mars and prior to breaking this connection, the thermal strap acts as a heat leak from the WEB. To prevent damage to components internal to the WEB, this strap is heated by the lander until the deployed configuration of MFEX is achieved,

Control and Navigation:

In performing its mission, MFEX must traverse to locations commanded as part of a once per sol sequence of commands from ground control. In order to accomplish a traverse the rover must determine:
> where to go: its goal location based on where it is,
> drive to the location,
> avoid hazards in route, and
> decide along the way if it is making timely progress to the goal location

For this last item, time is determined to a sufficient resolution to allow (with margin) the lander camera to image the rover in the terrain. This image becomes the planning image for the next sol of rover operation. This image must be captured in time to ensure that it can be communicated back to Earth on the same sol as when it is taken. This process allows the daily command sequence to be developed and transmitted in time for execution on the following sol.

MFEX performs traverses bawd on 'go to waypoint' commands in its daily command sequence. A 'go to waypoint' command contains as its goal an 'x,y' coordinate in a lander based coordinate system. [n executing this command, MFEX must regularly and autonomously update its position relative to the lander to determine (at a minimum) if it has reached the goal of its traverse. "I his update is accomplished through the processing of a combination of sensor measurements taken during the traverse. During the traverse, the vehicle odometer is updated using the encoder counts collected on each of the wheel actuators. A single encoder count is registered each time the motor shaft of the actuator completes a revolution. Given the gear ratio in the actuator, 2000 counts are registered cm a single wheel revolution. The counts accumulated on each of the six wheels are averaged to determine a change in the odometer. This averaged value (or change in the odometer) is used to update the estimated vehicle position in the lander coordinate system. This update occurs while the vehicle is stopped, about once each wheel radius (6.5cm) of distance traversed,

Another part of a traverse occurs as the rover turns. The command to 'turn' has parameters either a heading relative to a reference vector in the lander coordinate system or an angle relative to the current rover heading. From the current heading, a new heading is derived based on the commanded parameter. To achieve this heading, the four outside wheels are cocked to the 'steer-in-place' orientation. This is accomplished by driving the steering actuators to the appropriate position as measured by the potentiometers on each steering actuator. The vehicle is then driven until the commanded heading is achieved as measured from a rate gyro. This rate gyro is mounted to align its sensitive axis along the nominal vertical, allowing such a heading measurement to be made. Once the commanded heading is achieved, the integrated angular measurement from the gyro is used to update the vehicle heading reference.

Although 'go_ to_ waypoint' and 'turn' commands are generated by an operator to direct M FEX along a safe path to a goal location, obstacles along the lander camera line-of-sight and increased uncertainty as a function of distance from the lander can result in hazards for the vehicle unseen by an operator. As a consequence, MFEX is designed to autonomously find a safe path for traverse to the goal location. An on-board hazard detection function provides a means for evaluating for- safe traverse the terrain in front of the vehicle. A pair of cameras and an array of 5 laser light stripers provides the sensor for this hazard detection function. When a laser is powered, a nominally vertical plane of light is cast illuminating a part of the region in front of the vehicle. The cameras, with optics tuned to the wavelength of the lasers, image the illuminated terrain. Selected horizontal lines of the image are read anti processed. [displacement from a straight line cutting across these horizontal lines indicates the presence of an obstacle in the path. Each laser is powered in turn and the images in each camera processed. The results are correlated to develop a sparse map of obstacle distances and heights in front of the vehicle. 'I'he map is then assessed against the following criteria for assessing vehicle traverse :
        were scan line intersections missing indicating a possible hole or cliff?
        are the differences between lowest and highest height values above a threshold (not greater than a 35deg slope) indicating excessive slope?
        are the differences between two adjacent height values above a threshold (not greater than an wheel diameter) indicating a step-type hazard?
If any criteria fail, a hazard is declared

If a hazard is detected, MFEX autonomously notes the position of the hazard and turns to avoid it. 'i he hazard detection is repeated. Once a clear traverse is possible, the rover drives forward updating its position estimate until the hazard is past the midpoint of the vehicle (i. e., as determined from the current estimated rover heading and position compared to [he recorded position of the hazard). Once the hazard is past. MFEX turns toward the destination of the of go to waypoint' command and proceeds in its attempt to reach the goal of the traverse.

Additional tests are conducted as part of the hazard detection function. On-board accelerometers (one aligned to each axis of the vehicle) serve as a set of inclinometers, measuring the angle to the local gravity vector. An angle measurement beyond a threshold (not greater than a 35deg slope) represents an excessive

slope condition, The reaction o! the rover is to turn away from the hazard, traverse beyond then turn bath to the destination.

The hazard detection function is conducted once every wheel radius in length of traverse or before any turn. Power management concerns dictate that cameras and lasers cannot be used while the vehicle is moving. Hence, the rover exhibits a 'start-stop' behavior during traverses, with the vehicle moving a wheel radius then stopping to perform hazard detection/avoidance functions and update its position and heading estimates. The distance traveled between hazard detection/avoidance activities is a programmable parameter, which can be set by the operator. Depending on the assessment of the terrain at the console, the operator can change the distance parameter, lengthening the distance if the terrain is obstacle-free.

Vehicle motion control is accomplished through the on/off switching of the drive or steering motors. Motors are switched-on in pairs to minimize the size of the power-on transients. When turning, the center two wheels are modulated at a 50% duty cycle to prevent lifting of the front wheels and skidding in sharp curved turns when driving on a non-slip or high-slip surface. Each motor is individually protected from overheating and short circuits by the computer monitoring of current.

Computing Electronics:

MFEX computer control is implemented by an integrated set of computing and power distribution electronics. The computer is an 80C85 with a 2Mhz clock rated at 100Kips which uses, in a 16Kbyte page swapping fashion the memory provided in 4 different chip types ('Table 3).

Table 3 : MFEX memory

Size (Kbytes)	Type	Function
16	PROM, Harris 66i7	Boot code and ' Rover-Lite' backup code
64	RAM, IBM 2568	Main memory
i76	5, SEEQ 28C256 32Kbyte chips	Programs, patches and nonvolatile data storage
512	Micron MT1008 RAM	Temporary data storage

At boot up or upon reset the computer begins execution from the rad hard PROM. The programming stored in PROM loads programs into the rad hard RAM from non-volatile RAM. Program execution proceeds from the RAM. As commands are executed, other programming in non-volatile RAM is required and then swapped into the RAM for execution. To prevent excessive thrashing, some programs are executed from non-volatile RAM.

Programs are grouped into contexts, essentially by supported command type. Programs are swapped into RAM by contexts. The contexts are shown in Table 4 below:

Table 4 : Program Contexts

Context	Commands
General	main loop, APXS, MAE, set parameter. patch
Navigation	Goto waypoint, find rock, unstow, move. turn. health check, soii experiments
Imaging	capture image

The remainder of the electronics supports switching, power conditioning, and I/O channels. The I/O support is summaried in Table 5 below:

Table 5: MFEX I/O Electronics

Component	#	Comment
motor drives	11	FET switching
optical encoders	6	one for each wheel motor
potentiometers (HiRes)	3	12 bit differential measurement for bogeys and differential
potentiometers (LoRes)	5	8 bit measurement for steering actuators and APXS deployment mechanism
LED contact sensing	4	APXS deployment mechanism
temperature sensors	13	
current sensors	23	includes 11 actuator measurements
voltage sensors	24	includes analog measurements from the CCDs, gyro and accelerometers
serial ports	3	APXS, modem and GSE debug access
digital input bits	16	QCMS
interrupting digital bits	14	includes contact sensor interrupts
digital output bits	65	all component power switches
logic switches	31	
relays	3	APXS night mode and battery strings

At boot up or upon reset:
· The conditions which caused the reset to occur are determined based on the current state of selected memory locations and power conditions. Adequate power is either made available through battery engagement or is determined available from the solar panel.
· Program loading into rad hard RAM continues from the non-volatile RAM, including any commanded program patches.
· I/0 device hardware, watchdog timer and software error state counters are initialized.
· The rover clock is reset based on a successful communication with the lander requesting the current mission time.
· The current mission state is determined from the state of hardware flags anti/or a determination of the gravity vector from the accelerometers
· A health check is performed to certify the state of the I/O and power system. Upon success of the health check the basic control loop of the rover software system can be performed.

'The main rover control loop. executes until shutdown. Execution of this loop occurs at the rate of about once every 2 seconds (nominally, the watchdog timer cycle). Within this loop:
· Power and thermal management is performed. This includes: a determination if WEB heating should be performed, what power is available from the array, and an update of the battery use monitor - an estimate of energy available from the battery.
· If a load shed has occurred an extensive health check is performed to determine the device(s) which caused this condition.
' If no commands are queued for execution, the lander is checked for command loads.
' If command sequences are queued for execution and if no pending command loads are available on the lander. the next command is readied for execution. Prior to execution. error state conditions, timeout conditions and power availability are checked and parameters set to control the command execution. This setup includes identifying the telemetry collected during the execution.
· Once a command is executed successfully, the telemetry is packaged and sent to the lander. If an error occurs during the command an error report is prepared as telemetry and this report is sent to the lander
· With no command available for execution, the lander' is periodically interrogated for new command loads. In this control loop the timer (nominally 10min) for this interrogation is updated.
· If it is time for shutdown, the shutdown process is executed.

Shutdown occurs as the consequence of a timeout or a reduction in solar panel power output below the threshold level required for operation. Prior to shutdown. the next wakeup time is set on the alarm clock. Shutdown is accomplished with the removal of battery backup power to the main electrical bus. If the

rover is operating under battery power, this switch opening causes execution to cease immediately. It the rover is operating under solar power, shutdown will occur when solar power above a sufficient threshold ceases to be available. In the meantime, the computer is placed in an idle loop in which the watchdog timer is serviced.

All rover functions result from the execution of commands. All commands result in the generation of telemetry. In general, data collected as telemetry by the rover supports science. technology and mission experiments. On average approximately 6Mbit of telemetry is expected to be generated each sol; about 0.5Mbit constitutes engineering measurements, the remainder of the telemetry is comprised of images from the rover cameras. The available data rate of 14.4Mbit is based on continuous 2 hour transmission between the rover and lander, where the effective data transmission rate is 2Kbps.

Telecommunications:

Command and telemetry is provided by radio moderns on the rover and lander. This radio link utilizes a commercial modem operating at approximately 459.7MHz. It provides a 500m clear-field range, delivers 100mW radiated power. Communication rates with these devices are at 9600baud with effectively 2Kbps net data rate considering protocol overhead. When deployed, 30cm high whip antennas on the rover and the lander permit line-of-sight broadcasting. In tests on earth, a bit error rate for the modems has been measured to be 10E-5 within the nominal operating range of the rover. An RG 178 coax (0.085in diameter, 14 grams, 1.2dB loss) is routed approximately 1.5m from the WEB to the base of the rover UHF antenna assembly, and up the antenna assembly's mast. The assembly is sized to put the base of the deployed antenna approximately (one wavelength) above the Martian surface The lander-mounted UHF antenna assembly is attached to the lander low-gain antenna (LGA). A coax ("STORM 421-01 O," 0.21in diameter, 65 gram/meter, 0.25 dB loss/meter) cable is routed approximately 2m to the base of the UHF antenna assembly from the modem in the lander thermal enclosure. This antenna is mounted in a 2.5cm standoff configuration from the LGA and is attached 30cm below the antenna's radiating element.

The rover is the link commander of the half-duplex, UHF system. During the day, the rover regularly requests transmission of any commands sent from Earth and stored on the lander. When commands are not available, the rover transmits any telemetry collected during the last interval between communication sessions. The telemetry received by the lander from the rover is stored and forwarded to the Earth in the same manner as any lander telemetry. In addition, this communication system is used to provide a 'heartbeat' signal during vehicle driving. While stopped the rover sends a signal to the lander. Once acknowledged by the lander, the rover proceeds to the next stopping point along its traverse.

Operations:

Communication between the lander and Earth is provided twice each sol for nominally two hours during each period. The command and telemetry functions of the rover are designed to work within these communication constraints. Commands are generally designed at a 'high-level' (for example, 'go to waypoint') and are collected into a sequence for execution by the rover. The sequence is sufficient to carry out the mission functions of the rover on the given sol of issuance. Telemetry is collected during the execution of these commands and is transmitted to the lander. The lander stores this data and forwards the in format ion to Earth during a communication opportunity (perhaps not until the next sol).

Commands for the rover are generated and analysis of telemetry is performed at the rover control workstation, a silicon graphics workstation which is a part of the MPF ground control operation. At the end of each sol of rover traverse, the camera system on the lander takes a stereo image of the vehicle in the terrain. Those images, portion so a terrain panorama, and supporting images from the rover cameras are displayed at the control workstation. Modeled on the technology of 'computer-aided remote driving', the operator is able to designate points in the terrain on the displayed images. These points serve as goal locations for rover traverses. The coordinates of these points are transferred into a file containing the commands for execution by the rover-on the next sol. in addition, the operator can use a model of the vehicle which, when overlaid on the image ot'the vehicle, measures location and heading "1his

information is also transferred into the command file to be sent to the rover on the next sol to correct any navigation errors. 'I his command file is incorporated into the lander command stream and is sent by the MPF ground control to the lander, earmarked for transmission to the rover.

Status:

MFEX was integrated with the MPF lander at Cape Canaveral in late October, 1996. The combined system was successfully launch aboard a Delta II on December 4, 1996 and successfully landed on Mars on July 4, 1997. At this writing, MFEX has driven 80m on the surface of Mars; deployed the APXS and obtained measurements on 4 rocks and 6 soil areas; captured 36 stereo, 22 color and 7 monocular engineering images; has characterized its engineering subsystems verifying the designs described above; and gathered data supporting investigations in soil properties, geochemistry and geomorphology at the landing site, MFEX continues operating on the surface of Mars to aid in the science objectives of the MPF mission and in providing data which will aid in the design of future rovers.

Acknowledgment:

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